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Erratum: Feynman rules for the rational part of the Electroweak 1-loop amplitudes

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Abstract: We present the complete set of Feynman rules producing the rational terms of kind R_2 needed to perform any 1-loop calculation in the Electroweak Standard Model. Our results are given both in the 't Hooft-Veltman and in the Four Dimensional Helicity regularization schemes. We also verified, by using both the 't Hooft-Feynman gauge and the Background Field Method, a huge set of Ward identities -up to 4-points- for the complete rational part of the Electroweak amplitudes. This provides a stringent check of our results and, as a by-product, an explicit test of the gauge invariance of the Four Dimensional Helicity regularization scheme in the complete Standard Model at 1-loop. The formulae presented in this paper provide the last missing piece for completely automatizing, in the framework of the OPP method, the 1-loop calculations in the $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ Standard Model.

By comparing with an independent computation we performed in a general R_ξ gauge, and thanks to Huasheng Shao, that recomputed, independently of us, all of the R_2 effective vertices in the 't Hooft-Feynman gauge, we found a few problems in our formulae. We would like to correct them here.

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The vertex $Al\bar{l}$ in eq. (3.6) should read

$$
\begin{aligned}
Al\bar{l} \ \ : \ \ C_- &= \frac{1}{4}\left[\frac{(1+\lambda_{HV})\,Q_l^3}{4c_w^2} + \frac{m_l^2}{8s_w^2 m_W^2}\left(\frac{Q_l}{4} + Q_l I_{3l}^2\right)\right] \\
C_+ &= \frac{1}{4}\left[\frac{(1+\lambda_{HV})\,Q_l^3}{4c_w^2} - \frac{(1+\lambda_{HV})\,Q_l^2 I_{3l}}{2c_w^2} + \frac{(1+\lambda_{HV})\,Q_l I_{3l}^2}{4s_w^2 c_w^2}\right. \\
&\qquad \left. + \frac{1}{4s_w^2}\left(\frac{m_l^2 Q_l\left(1+4I_{3l}^2\right)}{8m_W^2} - \frac{(1+\lambda_{HV})}{2}\right)\right].
\end{aligned}
$$

The vertex $Z\phi^+\phi^-$ in eq. (3.8) should read

$$
\begin{aligned}
Z\phi^+\phi^- : \ \ C = \frac{i}{48 s_w c_w}&\left\{\frac{1-24c_w^4}{16c_w^2 s_w^2} + \frac{1}{m_W^2}\left(-\sum_{i=1}^{3}\left(m_{e_i}^2\left(Q_{e_i} + \frac{I_{3\nu_i}}{s_w^2}\right)\right)\right.\right. \\
&\left.\left. + N_{\mathrm{col}}\sum_{i,j=1}^{3}\left(V_{u_i d_j}V^\dagger_{d_j u_i}\left[(m_{u_i}^2 + m_{d_j}^2) + \frac{m_{u_i}^2 I_{3d_j} - m_{d_i}^2 I_{3u_i}}{s_w^2}\right]\right)\right)\right\}.
\end{aligned}
$$

Eq. (3.16) should be replaced by

$$
\left.\begin{array}{l} H\chi AA \\ H\chi AZ \\ H\chi ZZ \\ H\chi W^+W^- \end{array}\right\} : \ \ C = 0
$$

$$
\left.\begin{array}{l} HHAA \\ \chi\chi AA \end{array}\right\} : \ \ C = \frac{1}{16s_w^2}\left\{\frac{1}{12} - \frac{1}{m_W^2}\left[\sum_{i=1}^{6}\left(Q_{l_i}^2 m_{l_i}^2\right) + N_{\mathrm{col}}\sum_{i=1}^{6}\left(Q_{q_i}^2 m_{q_i}^2\right)\right]\right\}
$$

$$
\begin{aligned}
\left.\begin{array}{l} HHAZ \\ \chi\chi AZ \end{array}\right\} : \ \ C = \frac{1}{16s_w}&\left\{\frac{4+s_w^2}{12s_w^2 c_w} + \frac{1}{m_W^2 c_w}\left[\sum_{i=1}^{6}\left(Q_{l_i}m_{l_i}^2\left(\frac{I_{3l_i}}{2s_w^2} - Q_{l_i}\right)\right)\right.\right. \\
&\left.\left. + N_{\mathrm{col}}\sum_{i=1}^{6}\left(Q_{q_i}m_{q_i}^2\left(\frac{I_{3q_i}}{2s_w^2} - Q_{q_i}\right)\right)\right]\right\}
\end{aligned}
$$

$$
\begin{aligned}
\left.\begin{array}{l} HHZZ \\ \chi\chi ZZ \end{array}\right\} : \ \ C = -\frac{1}{16c_w^2}&\left\{\frac{1+2c_w^2+40c_w^4-4c_w^6}{48s_w^4 c_w^2}\right. \\
&+\frac{1}{m_W^2}\left[\sum_{i=1}^{6}\left(m_{l_i}^2\left(Q_{l_i}^2 + \frac{4I_{3l_i}^2}{3s_w^4} - \frac{Q_{l_i}I_{3l_i}}{s_w^2}\right)\right)\right. \\
&\left.\left. + N_{\mathrm{col}}\sum_{i=1}^{6}\left(m_{q_i}^2\left(Q_{q_i}^2 + \frac{4I_{3q_i}^2}{3s_w^4} - \frac{Q_{q_i}I_{3q_i}}{s_w^2}\right)\right)\right]\right\}
\end{aligned}
$$

$$
\begin{aligned}
\left.\begin{array}{l} HHW^-W^+ \\ \chi\chi W^-W^+ \end{array}\right\} : \ \ C = -\frac{1}{48s_w^4}&\left\{\frac{1+38c_w^2}{16c_w^2}\right. \\
&\left. + \frac{1}{m_W^2}\left[\sum_{i=1}^{3}m_{e_i}^2 + N_{\mathrm{col}}\sum_{i,j=1}^{3}\left(V_{u_i d_j}V^\dagger_{d_j u_i}\left(m_{u_i}^2 + m_{d_j}^2\right)\right)\right]\right\}
\end{aligned}
$$

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$$\left.\begin{array}{r} H\phi^+W^-A \\ \phi^-HAW^+ \end{array}\right\} : \quad C = K_1$$

$$\chi\phi^+W^-A \quad : \quad C = -iK_1$$

$$\phi^-\chi AW^+ \quad : \quad C = iK_1$$

$$\left.\begin{array}{r} H\phi^+W^-Z \\ \phi^-HZW^+ \end{array}\right\} : \quad C = K_2$$

$$\chi\phi^+W^-Z \quad : \quad C = -iK_2$$

$$\phi^-\chi ZW^+ \quad : \quad C = iK_2$$

$$\begin{aligned}
\phi^-\phi^+AA \quad : \quad C = & -\frac{1}{12s_w^2}\left\{\frac{1+21c_w^2}{16c_w^2} + \frac{1}{m_W^2}\left[\sum_{i=1}^{3} m_{e_i}^2\right.\right. \\
& \left.\left. + \frac{5}{6}N_{\rm col}\sum_{i,j=1}^{3}\left(V_{u_i d_j}V^\dagger_{d_j u_i}(m_{u_i}^2 + m_{d_j}^2)\right)\right]\right\}
\end{aligned}$$

$$\begin{aligned}
\phi^-\phi^+AZ \quad : \quad C = & \frac{1}{12s_w c_w}\left\{\frac{42c_w^4 - 10c_w^2 - 1}{32s_w^2c_w^2}\right. \\
& - \frac{1}{m_W^2}\left[\sum_{i=1}^{3}\left(m_{e_i}^2 Q_{e_i}\left(Q_{e_i} + \frac{5}{8}\frac{I_{3\nu_i}}{s_w^2}\right)\right)\right. \\
& + N_{\rm col}\sum_{i,j=1}^{3}\left[V_{u_i d_j}V^\dagger_{d_j u_i}\left(m_{u_i}^2\left(\frac{5}{6} - \frac{I_{3d_i}}{s_w^2}\left(Q_{d_j} - \frac{5}{8}Q_{u_i}\right)\right)\right.\right. \\
& \left.\left.\left.\left. + \; m_{d_j}^2\left(\frac{5}{6} - \frac{I_{3u_i}}{s_w^2}\left(Q_{u_i} - \frac{5}{8}Q_{d_j}\right)\right)\right)\right]\right]\right\}
\end{aligned}$$

$$\begin{aligned}
\phi^-\phi^+ZZ \quad : \quad C = & \frac{1}{12c_w^2}\left\{\frac{-1+2c_w^2+44c_w^4-84c_w^6}{64s_w^4c_w^2}\right. \\
& - \frac{1}{m_W^2}\left[\sum_{i=1}^{3}\left(m_{e_i}^2\left(Q_{e_i}^2 + \frac{5}{4}\frac{Q_{e_i}I_{3\nu_i}}{s_w^2} + \frac{I_{3\nu_i}^2}{s_w^4}\right)\right)\right. \\
& + N_{\rm col}\sum_{i,j=1}^{3}\left[V_{u_i d_j}V^\dagger_{d_j u_i}\left(m_{u_i}^2\left(\frac{5}{6} - \frac{I_{3d_i}}{s_w^2}\left(2Q_{d_j} - \frac{5}{4}Q_{u_i}\right) + \frac{I_{3d_i}^2}{s_w^4}\right)\right.\right. \\
& \left.\left.\left.\left. + \; m_{d_j}^2\left(\frac{5}{6} - \frac{I_{3u_i}}{s_w^2}\left(2Q_{u_i} - \frac{5}{4}Q_{d_j}\right)\right) + \frac{I_{3u_i}^2}{s_w^4}\right)\right]\right]\right\}
\end{aligned}$$

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$$
\begin{aligned}
\phi^-\phi^+W^-W^+ \quad : \quad C = & -\frac{1}{48s_w^4}\left\{\frac{1}{m_W^2}\left[\left(\sum_{i=1}^{3} m_{e_i}^2\right.\right.\right. \\
& + N_{\rm col}\left.\left.\sum_{i,j,k,l=1}^{3}\left(V_{u_id_j}V^\dagger_{d_ju_k}V_{u_kd_l}V^\dagger_{d_lu_i}\left(m_{u_i}m_{u_k}+m_{d_j}m_{d_l}\right)\right)\right)\right] \\
& \left.+\frac{38c_w^2+1}{16c_w^2}\right\} .
\end{aligned}
$$

Eq. (3.17) should be replaced by

$$
\begin{aligned}
K_1 &= \frac{1}{24s_w^3}\left\{\frac{1+22c_w^2}{32c_w^2}+K\right\} \\
K_2 &= \frac{1}{24s_w^2c_w}\left\{\frac{1+21c_w^2-22c_w^4}{32c_w^2s_w^2}+K\right\} \\
K &= \frac{1}{8m_W^2}\left[\sum_{i=1}^{3} m_{e_i}^2+N_{\rm col}\sum_{i,j=1}^{3}\left(V_{u_id_j}V^\dagger_{d_ju_i}\left(3m_{d_j}^2+2m_{u_i}^2\right)\right)\right] .
\end{aligned}
$$

Eq. (3.18) should be replaced by

$$
\begin{aligned}
u\bar{u} \quad : \quad C_- &= \frac{1}{16}\left[(1+\lambda_{HV})\frac{Q_u^2}{c_w^2}+\frac{m_u^2}{2s_w^2m_W^2}\left(\frac{1}{2}\sum_{j=1}^{3}\left(V_{ud_j}V^\dagger_{d_ju}\right)+\frac{1}{4}+I_{3u}^2\right)\right] \\
C_+ &= \frac{1}{16}\left[(1+\lambda_{HV})\left(\frac{1}{c_w^2}\left(Q_u^2+\frac{I_{3u}^2}{s_w^2}-2Q_uI_{3u}\right)+\frac{1}{2s_w^2}\sum_{j=1}^{3}\left(V_{ud_j}V^\dagger_{d_ju}\right)\right)\right. \\
&\quad \left.+\frac{1}{2m_W^2s_w^2}\left(\frac{1}{2}\sum_{j=1}^{3}\left(V_{ud_j}V^\dagger_{d_ju}m_{d_j}^2\right)+m_u^2\left(\frac{1}{4}+I_{3u}^2\right)\right)\right] \\
d\bar{d} \quad : \quad C_- &= \frac{1}{16}\left[(1+\lambda_{HV})\frac{Q_d^2}{c_w^2}+\frac{m_d^2}{2s_w^2m_W^2}\left(\frac{1}{2}\sum_{i=1}^{3}\left(V_{u_id}V^\dagger_{du_i}\right)+\frac{1}{4}+I_{3d}^2\right)\right] \\
C_+ &= \frac{1}{16}\left[(1+\lambda_{HV})\left(\frac{1}{c_w^2}\left(Q_d^2+\frac{I_{3d}^2}{s_w^2}-2Q_dI_{3d}\right)+\frac{1}{2s_w^2}\sum_{i=1}^{3}\left(V_{u_id}V^\dagger_{du_i}\right)\right)\right. \\
&\quad \left.+\frac{1}{2m_W^2s_w^2}\left(\frac{1}{2}\sum_{i=1}^{3}\left(V_{u_id}V^\dagger_{du_i}m_{u_i}^2\right)+m_d^2\left(\frac{1}{4}+I_{3d}^2\right)\right)\right] .
\end{aligned}
$$